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# **Salinity Measurements in the Coastal Ocean**

## **Workshop Review**

**September 14-15, 1998**

Catherine Woody<sup>1</sup>, Eddie Shih<sup>2</sup>, Jerry Miller<sup>3</sup>, Thomas Royer<sup>4</sup>,  
Larry P. Atkinson<sup>4</sup>, Richard S. Moody<sup>4</sup>

Co-sponsored by

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and the

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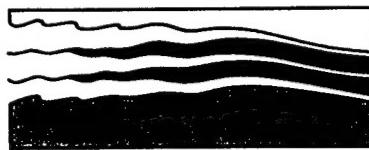
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**CENTER FOR COASTAL PHYSICAL OCEANOGRAPHY**

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# Salinity Measurements in the Coastal Ocean

## Workshop Review

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## COASTAL SALINITY WORKSHOP

### REVIEW INTRODUCTION

The importance of salinity measurements in understanding coastal ocean processes has been long recognized. Unfortunately, the frequency of such measurements has decreased considerably in the past years, for a number of reasons. Salinity measurements are now made routinely at very few places, and there is no logical plan for where salinity measurements should be made or how frequently. We feel it is urgent that the United States initiate a modest salinity measuring program using existing technology and locations.

To address the immediate national needs for salinity measurements in the coastal ocean, a workshop was held September 14-15, 1998, in Hampton, Virginia. The goals of the workshop were:

- \$ Establish acceptable techniques based on needed accuracy and cost-efficiency.
- \$ Establish criteria for location and frequency of salinity measurements.
- \$ Inventory all existing coastal salinity measurements.
- \$ Identify users of coastal salinity and derivative data (density, stratification, coastal currents, etc.).
- \$ Determine requirements to be addressed by new technology.

### Summary of Recommendations

**Statement of Importance of Salinity Measurements** - Because of its large dynamic range in the coastal ocean, salinity is a critical variable for understanding and predicting biological and physical processes and their interactions with the food web, climate, weather, and commerce. In estuaries, salinity becomes important for drinking water intakes and agricultural activities.

**Statement on Need for Accuracy** - For coastal waters with a high variance in salinity, the workshop participants agreed that the desired short-term goal for an in situ salinity sensor is to be capable of measuring salinity to 0.1 accuracy on the Practical Salinity Scale and maintain stability for a minimum of 6 months. It is to be portable, low cost, low power, and non-fouling. The long-term goal is to improve the accuracy to 0.01 psu with a range of values between 0.1 and 42 on the Practical Salinity Scale.

**Statement on Needs in Anti-fouling** - A current requirement is to deploy sensors to accurately collect data for six months, with a long-term goal of one year. Improved anti-fouling technology needs to be developed to make long term, in situ salinity measurements possible without harming the environment.

**Statement on Needs in Remote Sensing Technology** - Once the capability is operational, remote sensing will provide a cost effective mechanism to map surface salinity to aid in understanding coastal processes.

**Statement on Coordination** - coordination of effort to enhance salinity measurements will provide the

*following:*

- \$ Information on technical issues such as fouling
- \$ Comparative information on sensor systems
- \$ Coordination of calibration and quality assurance procedures
- \$ Information on and location of available data
- \$ Development of archiving scheme for data at NODC

### **Why Salinity?**

Salinity has always been recognized as important in the high latitude and coastal regions, but the interest of the science community in measurements of salinity has varied from one decade to another and from one region to another. A recent workshop on the future of the National Science Foundation programs in physical oceanography, APROPOS, identified global salinity measurements as one of several goals for the field. Longtime series measurements were also identified as being important to climate studies. While the community has concentrated on global heat flux measurements such as those in the WOCE program, much less attention has been devoted to the salt budget. The vast majority of global precipitation occurs over the ocean, so knowledge of sea surface salinity could lead to better estimation of the global hydrological cycle and a better understanding of the most important greenhouse gas, water vapor. In the next decade, global hydrology will probably play an important role in international conflicts, as population increases and precipitation changes cause food shortages in some regions. Today there are some areas in the world where armed conflicts over water rights might soon take place. Oceanographers need to work with hydrologists to understand this very serious problem.

In the past decade many regions in the world's oceans have experienced a decline in salinity and accompanying changes in the mixed layer depth. This is particularly true for the North Pacific where the mixed layer depth at Ocean Station P (50 N, 145 W) has decreased at a rate of about 63 m/century. Elsewhere in the coastal North Pacific, the mixed layer depth has been decreasing at a rate of about 32 m/century. The coastal salinity as measured at Canadian lighthouse stations is decreasing at rates that vary from 1 to about 0.5 psu per century. However, at one location, the sea surface salinity has decreased by about 1 in the last five years. The United States oceanographic community is now recognizing the importance of long-term salinity measurements. There are urgent needs to initiate global ocean sampling programs for temperature and salinity. Such programs are critical to understanding ocean and atmosphere climate variability and their causes.

To understand coastal processes, salt content and temperature of coastal waters are two fundamental parameters that must be measured, each providing different clues as to the processes at work in the system. Temperature provides information related to heat exchange, while salinity provides information about movement and dilution of waters in the coastal ocean. Integrated, they are indicators of transport, mixing, stratification, and frontal boundaries. Thus salinity gives us unique and easily acquired

information about issues of great importance to the coastal ocean.

Because of the stability of salinity in the open ocean, it is a good indicator of global warming, changes in circulation, and air/sea interaction. These, however, are harder to detect in coastal waters due to the wide range of salinity and annual variability in precipitation/runoff. In fact, the need for salinity measurements in coastal oceans is quite varied, and, it was agreed by the workshop attendees, that there were not enough long-term salinity measurements to adequately address the problems. It is well known that runoff from land is changing in many areas, and resultant salinity will be lowered which will no doubt have significant effects on all aspects of coastal waters.

The following list of important processes, created during the workshop, require knowledge of salinity:

#### I. Biological Effects

A. How does salinity affect ecosystem functions in the following areas?

- \$ Coral growth
- \$ Oyster disease
- \$ Coastal wetlands including flood water transport
- \$ Nursery grounds

B. Why is salinity important in the development of harmful algal blooms?

- \$ Salinity becomes an important habitat parameter by controlling the development of algal blooms as >salinity barriers= or fronts are developed in estuaries or coastal waters.

C. How does aquaculture site selection critically depend on salinity variability?

#### II. Physical Processes

A. How will changes in runoff, and hence salinity, affect the following processes in the coastal ocean?

- \$ Strength of coastal currents
- \$ Change of mixed layer depth
- \$ Change in stratification and buoyancy fluxes
- \$ Change in internal wave regime with change in stratification
- \$ Change in gas exchange processes
- \$ Change in steric sea level

B. What are the potential problems with altered runoff?

- \$ Salt wedge changes in estuaries affect sediment deposition patterns, which impact dredging operations.
- \$ Salinity is key to understanding the implications of controlling river flow for such operations as dam construction and removal.
- \$ Salinity is important in determining the survival of invasive species from ballast water discharge and suitable locations for ballast water exchange.
- \$ The direct impact of salinity on water density affects a ship=s draft and therefore its commercial load capacity.

### C. What are the global impacts?

\$ Heat Cycle

\$ Circulation

\$ Sea level

\$ Hydrological cycle - change on a global scale affects the freshwater content of coastal ocean waters. Salinity measurements are key in determining these effects.

\$ Episodic events (El Nino/La Nina cycle) cause runoff variability and extreme changes in coastal salinity

#### *Statement of Importance of Salinity Measurements*

*Because of its large dynamic range in the coastal ocean, salinity is a critical variable for understanding and predicting biological and physical processes and their interactions with the food web, climate, weather, and commerce. In estuaries, salinity becomes important for drinking water intakes and agriculture activities.*

### **History of Salinity Measurements**

The saltiness of ocean waters has been recognized throughout recorded history. Many of the early investigations on salt in the ocean focused on the measurement of those salts. Scientific work on ocean salts was first done by Robert Boyle in 1674 with his publication of *Observations and Experiments on the Saltiness of the Sea* (Birch, 1965). The paper was the result of a general interest in natural waters rather than advancement of seawater chemistry (Wallace, 1980). His measurements of the salt in seawater were done both by evaporating a pound of seawater and by precipitating the salt. He favored the latter process and recommended the use of silver nitrate to determine the sweetness of all waters (Boyle, 1693). For the next century, no systematic studies of sea water salts were done using a common analytic scheme. Late in the 18th century, Lavoisier (1772) used evaporation with a solvent extraction to obtain data for his analysis of sea water. Bergman (1774) used evaporation and precipitation to carry out a detailed examination of all natural waters and developed a list of the substances that he had identified in sea water. He introduced the technique of weighing the precipitated salts to determine their concentrations (Wallace, 1980). Gay-Lussac (1817) used titrimetry to develop simple and accurate

methods to determine the salts and concluded that the salt concentrations of open sea water were constant everywhere. Evaporation-solvent-extraction continued to be the primary method of determining saltiness until Murray (1818) introduced the indirect method involving the precipitation of specific acids and bases, @ then inferring the constituents of sea salt.

These early works on sea salt led to the work of Georg Forchhammer (1865) who introduced the term Asalinity@ and determined 27 elements in sea water. He also introduced the concept that while salinity in the open ocean might vary, the ratios of the various salts to each other would remain the same. From this he suggested that the determination of chlorine would be a means of rapidly determining salinity. It was the work of William Dittmar (1884) in his analysis of 77 samples from the *Challenger* expedition that was the most extensive treatment of salinity in that period and further established the idea of Aconstancy of composition." Knudsen, Forch, and Sorenson produced a gravimetric definition of salinity in terms of total halide content and the titrimetric procedure to determine chloride that was widely accepted (Knudsen, 1901). An International Council for the Exploration of the Sea commission headed by Prof. Knudsen recommended that the definition of salinity be as follows: AT the total amount of solid material in grams contained in one kilogram of sea water when all of the carbonate has been converted to oxide, all the bromine and iodine replaced by chlorine and all the organic material oxidized@ (Knudsen, et al., 1902). Various titration methods have been used for the determination of salinity but the most common one was the colorimetric titration/precipitation of halides using silver nitrate. Typical precision was generally better than +/- 0.02 ppt (Emery and Thomson, 1998).

The determination of salinity through the use of conductivity measurements was first recognized by Knudsen (1901) but was not developed until the 1950=s. At that time, a conductivity salinometer was developed for the International Ice Patrol that was capable of measuring salinity to better than 0.01 ppt (Emery and Thomson, 1998). It contained six thermostatically controlled conductivity cells and was claimed to have reached a precision of 0.003 ppt. (Cox, 1963). In addition to the higher precision afforded by conductivity determinations of salinity, conductivity measurements offered the potential of rapid, accurate profiling of the water column rather than only obtaining a few tens of discrete bottle samples. The first salinity-temperature-depth (STD) profiler used conductivity cells that had problems with fouling (Hamon, 1995). An STD with an inductive cell was soon developed that avoided the electrode fouling problem (Hamon and Brown, 1958). Problems with salinity "spiking" due to a mismatch of temperature and conductivity sensor response times and controversy over the algorithm used to calculate salinity have led to the return of the measurement of conductivity-temperature-depth (pressure) (CTD) by modern instruments. These instruments have a precision of better than 0.005 ppt. Table 1 lists the progression of salinity measurements

Table 1  
Chronology of Significant Instrumentation  
and Techniques for the Measurement of Salinity

Knudsen titration of chlorides	Knudsen, Norway 1901
Conductivity-type salinometer	Wenner, U.S. 1930
Index of refraction	Utterback, France 1934
Sea Going electrode <i>in situ</i>	Jacobson, U.S. 1948

Inductive-type salinometer	Esterson, U.S. 1957
Sea going bench salinometer	Brown and Hamon, AUS 1961
STD (inductive) <i>in situ</i>	Bisset-Berman Co, U.S. 1964
CTD (conductive) <i>in situ</i>	Kroebel, Germany 1973
CTD (conductive) <i>in situ</i>	NBIS, U.S. 1974
AUTOSAL laboratory	Dauphinee, Canada 1975
Index of refraction	Mahrt and Kroebel, Germany 1982

In concert with the higher precision of salinity determination, new definitions have been developed for the determination of salinity directly from conductivity. This is the Practical Salinity Scale (PSS-78) (Lewis, 1980). This definition is based on the ratio of the conductivity of the sample to the conductivity of standard seawater of 35 ppt. It is a practical scale in that it is removed from the original definition of salinity that is based on the salt content of the water sample ( Knudsen, et al., 1902).

Although the modern definitions of salinity from conductivity assume constancy of composition in the open ocean, that assumption is violated in coastal waters. The precision required for coastal salinity measurements is much less than that required for the open ocean because the variability of salinity in the coastal ocean is relatively large in both time and space. Therefore, less precise methods of measurement may be used. For example, salinities were frequently determined from density measurements using hydrometers and temperatures. This was done at coastal locations such as lighthouses around the United States and Canada and continues to be done at Canadian lighthouses. The accuracy is of the order of +/-0.2 psu. The difficulty in measuring salinity, in comparison with temperature measurements, has resulted in a dearth of salinity measurements, sometimes inaccurate and/or using unproven techniques. The latter was true in the 1970's with the introduction of STD's. It promised detailed vertical profiling that was impossible with discrete bottle sampling. As it often turned out, there were many samples per depth but their accuracies were much less than those obtained with bottles and salinometers. As a result, much hydrographic data using STDs and early CTD's from that era is suspect.

Additionally, difficulty in taking salinity measurements frequently prohibits their incorporation in an ocean sampling scheme. For example, upper layer thermal structure has been measured for decades using mechanical bathythermographs (BT) or expendable bathythermographs (XBT) and even aircraft deployed XBT's (AXBT). These temperature measurements have routinely been taken from merchant vessels and military platforms. The military interest is not necessarily in the temperature structure but rather in the distribution of sound speed in the upper ocean layers for submarine detection. However since salinity does not affect sound velocity to a great extent in the open ocean, it was not necessary to include it. So, we have decades of temperature measurements over the global ocean taken by many different organizations, but global salinity measurements have generally only been made from research vessels. Now that the Navy is more keenly interested in coastal regions, the importance of the effect of salinity on sound speed has been recognized. So that we might begin to survey global sea surface salinity, simpler techniques, such as the XBT for temperature, are needed to measure salinity from ships of opportunity or through remote sensing.

## **Present Technology for Salinity Measurements**

Salinity is routinely measured in two ways. The first and more traditional method is through collection of water with bottles and analyses done with a laboratory salinometer. While this method is considered the most accurate and precise, it is the most time consuming and labor intensive. The second is by direct CTD measurements. CTD sensors are presently used routinely in the field for surveying and monitoring. This is done using a profiling CTD or moored *in situ* conductivity-temperature (CT) sensor. Some are partially calibrated electronically in the laboratory, but ultimately all are put in a temperature controlled salt water bath and calibrated with bottle samples/laboratory salinometers or with a higher accuracy conductivity sensor.

Salinity values can range from 0.001 to 45 on the Practical Salinity Scale in the coastal areas, but the present salinity definition only covers a range of 2 to 42. Most CT=s could cover the wider range with an expanded salinity definition.

The workshop attendees posed the following questions regarding sensor technology:

- \$ What are the characteristics of the salinity sensor?
- \$ What is a reasonable length of time between servicing?
- \$ What is acceptable for drift, precision, and accuracy?

### ***Statement on need for accuracy***

*For coastal waters with a high variance in salinity, the workshop participants agreed that the desired short-term goal for an in situ salinity sensor is to be capable of measuring salinity to 0.1 accuracy on the Practical Salinity Scale and maintain stability for a minimum of 6 months. It is to be portable, low cost, low power, and non-fouling. The long-term goal is to improve the accuracy to 0.01 with a range of values between 0.1 and 42 on the Practical Salinity Scale.*

## **Anti-fouling techniques and Issues**

Long term, *in situ* sensors suffer from fouling, the major problem in coastal programs. High biological growth can severely alter sensor geometry. After application, antifoulant paints also can alter the geometry through degradation of the paint itself. An accuracy of 0.1 is attainable for short deployments (weeks), but, even with the best anti-fouling techniques, accuracy degrades to worse than 1.0 for deployments of several months.

Presently tri-butyltin (TBT) is the most effective antifoulant material but has strict environmental controls for permitting and use. Some states will allow limited use of TBT with strict guidelines. With antifoulant treatment, salinity sensors presently can operate for up to 3 months in coastal waters and 2.5 years in deep water before severe accuracy degradation occurs.

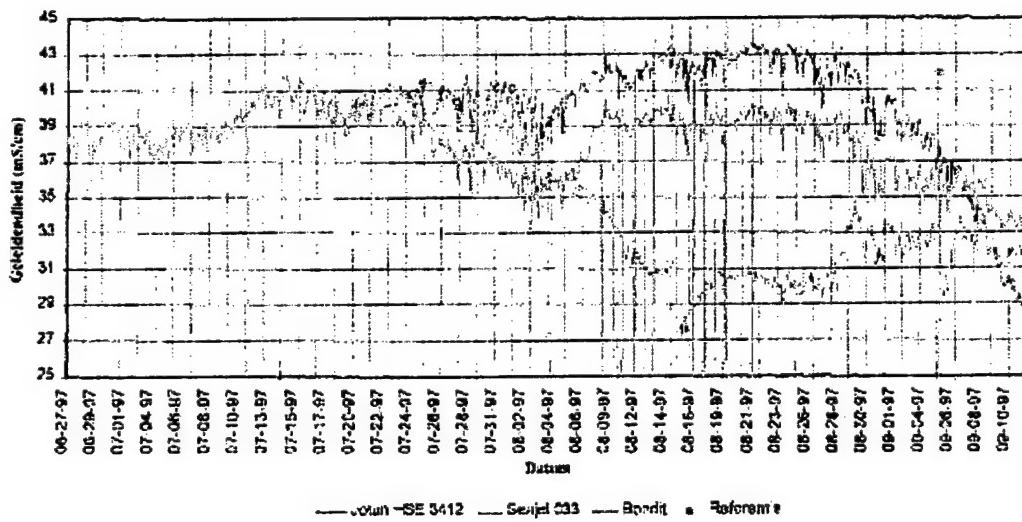
The following issues and questions were presented for further investigation:

- \$ There is presently no known review for antifoulants and their effectiveness.
- \$ How do we prevent fouling?
- \$ What are the legal issues of using TBT, and what recommendations should be made?
- \$ Where should research and development focus - on new technology or environmentally safe and effective antifoulants?
- \$ A clearinghouse on bio-fouling of sensors needs to be established.

There are few studies available on antifoulants and their effects on sensors and data. One such study was conducted in the Netherlands to select a suitable sensor to measure conductivity and temperature for continuous, *in situ* monitoring of coastal waters (van Oort, *et al.*, 1998). Upon selection of the sensor, further studies were conducted on the effects of three different antifoulant paints on the sensor. Bondit B2/C6 (based on ammonium hydroxide), Seajet 033 (30-60% cupricoxide and 10-30% xylene), and Jotun HSE 3410 (0-1% tri-butyltin and 30-60% cupricoxide) were used with one sensor free of antifoulant used for visual comparison only. The field tests were conducted in brackish, somewhat stagnant water. The results of the tests are shown in Figure 1. Conductivity data was recorded from the three test cases with reference conductivity measured weekly using a hand-held sensor of WTW, model LF196. The results showed Jotun HSE 3412 to be the most effective, and it was found that the use of antifoulant paint increased the maintenance-free period for about a week. The authors did not feel that this time increase was enough to justify the use of the antifoulant for open ocean or coastal water.

Figure 1.

Antifoulingtest GenT  
Bruinisse, 27-06 t/m 12-09-97

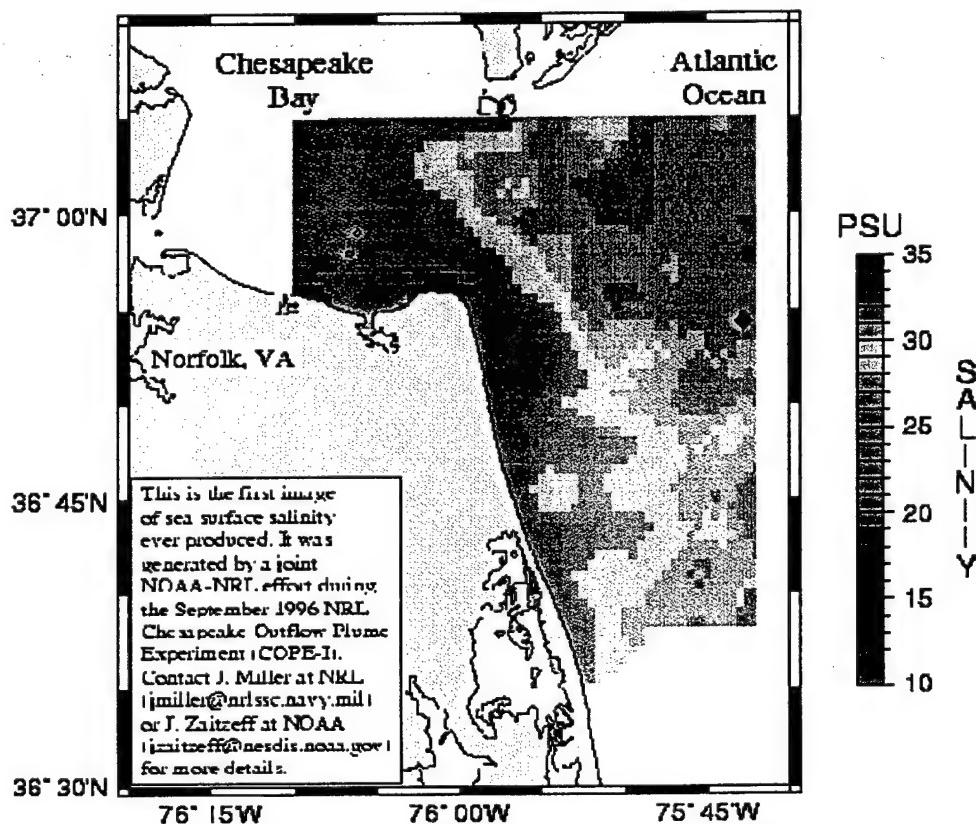


### **Statement on Needs in Anti-fouling:**

*It is presently desired to deploy sensors to accurately collect data for six months with a long-term goal of one year. Improved anti-fouling technology needs to be developed to successfully complete long term, in situ salinity measurements without harming the environment.*

### **Future Technology - Remote Sensing**

Remote sensing offers a solution to the fouling problem but presents technological challenges. Such technology is now available for research and development but is a long way from routine use. It is estimated that in 5 to 10 years, an instrument may be available for routine measurements.



**Figure 2. Microwave Sensing of Sea Surface Salinity**

Images of coastal and estuarine surface salinity have been produced using L-Band microwave signals remotely sensed from aircraft. An airborne swath-scanning surface salinity mapper (Miller *et al.*, 1998) has been flown successfully in several coastal environments along the east coast of the US (Figure 2). For typical sampling scenarios, salinity noise levels are a few tenths for 1x1 km pixels. The next generation of this instrument has already been designed and components tested. Expected noise levels will approach 0.1 psu for single 1-second realizations and less for 1x1 km pixel averages. This new remote sensing capability provides a means of substantially advancing our understanding of physical processes in the coastal zone where traditional moored and ship-based observations are compromised due to the prevailing short temporal and spatial scales.

Salinity images have been generated for the tropical waters of Florida Bay and for the temperate Chesapeake Bay under a variety of atmospheric and hydrologic forcing conditions. These data reveal local flow regimes and provide the basis for diagnostic calculation of associated low-frequency velocity fields. When combined with other data (e.g., ocean color, radar-derived surface currents, suspended sediments), details of linear and non-linear biogeophysical processes can be addressed.

Implementation of this technology on satellites for global imaging of salinity is possible. Beyond salinity, this technology can be used to estimate soil moisture and to map the extent of sea ice and oil spills. Existing airborne instruments are being used as test-beds for satellite engineering studies. They also constitute the basis for development of simple, inexpensive sensors which can be mounted on buoys and other available coastal and estuarine platforms. Deployed in the air, these will be naturally free of fouling.

### ***Statement on Needs in Remote Sensing Technology***

*Once operational, remote sensing will provide a cost effective mechanism to map surface salinity to aid in understanding coastal processes.*

### **Criteria for Salinity Measurements**

Due to the large variability in coastal and estuarine waters, the following questions were posed concerning the location for measurements:

- \$ What should the criteria for salinity observations be for coastal waters?
- \$ What are the models that require salinity measurements and what locations for salinity measurements are needed to satisfy those needs?

Major features such as coastal currents, plumes from estuaries and rivers, and critical habitats were listed as important criteria for deciding the location of measurements. Large scale sampling may be required to identify the boundaries of such features and to monitor variability. Length scales for along-shore and cross-shelf need to be defined.

While a monitoring system cannot be expected to provide detailed coverage of salinity structure throughout the coastal ocean, it should be capable of revealing large-scale and qualitative changes in coastal salinity conditions. Spatial distribution of salinity sensors should be such that cross-shelf and along-shore variability of coastal currents which transport larvae, nutrients, and contaminants is qualitatively indexed. To achieve such coverage, one should deploy sensors a few baroclinic Rossby radii offshore as well as within one radius of shore. As for along-shore spacing, the larger salinity-driven coastal currents (i.e., those most likely to significantly affect resources) have along-shore scales of one to a few hundred kilometers. A nominal spacing of 100 km is a reasonable target. Actual along shore spacing should be tailored to local conditions.

Numerical models complement field measurements in many ways. They provide information and forecasting capability over a wide area, predicting environmental conditions where observations are not available, as well as a better understanding of the physical phenomena in estuarine and coastal waters. Numerical models also guide field measurement planning.

Coastal and estuarine nowcast/forecast models consist of the laterally or vertically integrated two-dimensional (2-D) or three-dimensional (3-D), time-dependent, numerical hydrodynamic momentum equations, the continuity equation, and embedded equations of mass transport (e.g., salinity and temperature). The water density gradient induces gravitational circulation and affects the vertical mixing processes. It is related to the salinity and temperature through the equation of state. Output fields of water level, currents, salinity, and temperature are important input parameters to tide and current forecasts plus water quality, biological, and ecosystem models. For large ocean models, salinity is also an important parameter in determining mixed layer properties and dynamic height for velocity calculations. Salinity measurements used in estuarine and coastal nowcast/forecast models provide initial conditions, boundary conditions, model verification, and model improvement. In the data assimilation process, salinity data are used to improve initial conditions.

The capability of reproducing the long-term salinity regime has been demonstrated (Wang, Johnson, and Cerco, 1998, and Schmalz, *et al.*, 1994). Presently, many model simulations are made using salinity fields constructed by spatial and temporal interpolations of sparsely distributed historical data sets. For example, typical discrepancies between model simulation results and measurements for a Chesapeake Bay year-long simulation are in the order of 10% in the main bay and 15-20% in the tributaries (Johnson, *et al.*, 1991), and 1-4 on the Practical Salinity Scale RMS differences for a Galveston Bay simulation (Schmalz, 1996). Major sources of errors include lack of adequate and accurate salinity inputs and freshwater inflows and a lack of understanding of vertical mixing processes. Long-term, reliable, and adequate spatial distributions of salinity data are badly needed. Table 2 identifies the information needed for model input.

Table 2

**DESIRED MODEL INPUT**

Salinity Measurements	CTD	\$ Profiling  \$ Continuous, in situ  \$ accuracy of 0.01 psu
Location	Near River Inflows	\$ With estuarine regions
	Open Ocean Boundary	\$ 50-200 km offshore  \$ 100-200 km wide at bay entrance
Spatial Distribution	Horizontal	\$ Salinity gradients seaward  \$ Downstream end of tributaries
	Vertical	• Gradients and location of transition depth  \$ Surface, mid-depth, bottom
Temporal Distribution	Long-Time Series	\$ Flood, drought, tidal, seasonal, annual variability
Sampling Frequency	Hourly*	\$ Real time data collection and reporting (desirable for boundary conditions in some model simulations)
Data Quality	Uniform Methodology and Format	\$ Assure reliable data collection with known uncertainty bounds.

\* CT data are currently sampled at 6-minute intervals as currents and water levels at NOS automated PORTSÔ stations. This sampling interval is desirable for PORTSÔ application modeling.

Salinity, temperature, currents, and other hydrodynamic parameters are computed at different spatial resolutions in several NOAA models. The grid spacing is dependent on the particular estuary or coastal area. Generally, a model grid of 10 km near the coast and 20 km offshore is used for coastal models. A 3 to 10 km grid was used in Chesapeake Bay, and a 250 m to 3.5 km grid in Galveston/Houston Bay with a finer grid of 60 m to 1.3 km in shipping channels. In the New York/New Jersey Harbor a spacing of 50 to 750 m and finer were used for modeling. Underway towed salinity and temperature profiling systems have been useful in obtaining ocean boundary data with moored or CTD cast measurement to establish climatology. Real-time salinity data are presently being collected at a limited number of existing NOAA PORTSÔ sites and some C-MAN locations.

## Locations of Salinity Measurements

*Every marine laboratory is morally obligated to make salinity measurements.*

The following agencies and institutions are presently making salinity measurements:

*Federal Government:*

NOS - PORTSÔ (Physical Oceanography Real Time System)

**NOS PORTSÔ Sites**

Monitoring Stations	Stations with Salinity	PORTSÔ sites
12	6	San Francisco Bay
7	4	Houston/Galveston Bay
5	0	Tampa Bay
7	4	Chesapeake Bay
1	1	NY/NJ Harbor

NDBC - Florida Keys, Chesapeake Tower

NOS - Status and Trends program (300 coastal stations, salinity measurements collected once annually at 120 stations)

*States:*

*Alabama*

- Contact: Scott Brown
- Email: jsb@adem.state.al.us
- Phone: 334-450-3400

*Alaska*

- Contact: Shari Vaughan, Jeff Hock
- Email: vaughan@pwssc.gen.ak.us
- Suggested website: <http://www-water-ak.usgs.gov/Projects/nawqa.htm>

*California*

- Contact: Katherine Triboli
- Email: ktriboli@water.ca.gov
- Suggested websites:  
<http://iep.water.ca.gov/wqdata/>  
[http://ceres.ca.gov/catalog/bin/list\\_records?catalogue=125](http://ceres.ca.gov/catalog/bin/list_records?catalogue=125)

*Connecticut*

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- Phone: 860-424-3687

*Florida*

- Contact: J. Chris Humphrey
- Email: humphrey\_j@popmail.firn.edu
- Suggested websites: <http://comps.marine.usf.edu>

<http://coral.aoml.noaa.gov>

*Hawaii*

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*Louisiana*

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*Maryland*

- Contact: William D. Romano
- Email: Bromano@dnr.state.md.us
- Phone: (toll free) 877-620-8DNR ext. 8655
- Suggested websites:  
<http://www.chesapeakebay.net/bayprogram/data/infobase.htm>  
<http://www.chesapeakebay.net/bayprogram/data/wqual/baydots.gif>

*Massachusetts*

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*Texas*

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- Email: brock@twdb.state.tx.us
- Website: <http://www.twdb.state.tx.us/www/twdb/planning/environmental/envirosystem.html>

*Washington*

- Website: <http://inlet.geol.sc.edu/cdmoweb/html>

*Universities:*

*University of Alaska*

- Contact: Chirk C. Chu
- Email: [chu@ims.usf.edu](mailto:chu@ims.usf.edu)
- Phone: 907-474-7092
- Suggested websites:  
<http://www.ims.uaf.edu:8000/gak1>  
<http://www.ims.uaf.edu:8000/~chu>  
<http://www.ims.alaska.edu:8000/db.html>

*Oregon State University*

- Contact: Tony Watson
- Website: <http://www.hmsc.orst.edu/>

*Western Washington University*

- Contact: Gene McKeen
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*Non-profit Organizations:*

The National Association of Marine Laboratories (NAML), a non-profit consortium of over 120 member laboratories from Alaska to Puerto Rico, Guam to Bermuda, reports 73 labs taking salinity measurements:

ID#	INSTITUTE NAME	CITY	STATE
1161	BARUCH MARINE FIELD LAB-UNIV OF SOUTH CAROLINA	GEORGETOWN	SC
588	BODEGA MARINE LABORATORY	BODEGA BAY	CA
948	DEPT OF MARINE SCIENCE, UNIV OF SOUTH FLORIDA	ST PETERSBURG	FL
854	INST OF MARINE & COASTAL SCIENCES/RUTGERS UNIV	NEW BRUNSWICK	NJ
254	LYLE S. ST. AMANT MARINE LABORATORY	BATON ROUGE	LA
108	MOTE MARINE LABORATORY	SARASOTA	FL
617	OSU HATFIELD MARINE SCIENCE CENTER	NEWPORT	OR
27	RUTGERS UNIV MARINE FIELD STA.	TUCKERTON	NJ
453	UNIV OF MARYLAND CENTER FOR ENVIRONMENTAL SCIENCE/	CAMBRIDGE	MD
1162	BARUCH MARINE FIELD LAB-UNIV OF SOUTH CAROLINA	GEORGETOWN	SC
951	ACADEMY OF NATURAL SCIENCES, ESTUARINE RES. CENTER	ST. LEONARD	MD
695	DUKE UNIVERSITY MARINE LAB	BEAUFORT	NC
18	FLORIDA INSTITUTE OF OCEANOGRAPHY KEYS MARINE LABO	ST. PETERSBURG	FL
877	FLORIDA INSTITUTE OF TECHNOLOGY	MELBOURNE	FL
747	WILLIAM W. KIRBY-SMITH/DUKE UNIVERSITY MARINE LAB.	BEAUFORT	NC
811	HUMBOLDT STATE UNIV TELONICHER MARINE LAB	TRINIDAD	CA
1001	OREGON INST OF MARINE BIOLOGY, UNIV OF OREGON	CHARLESTON	OR
601	SHANNON POINT MARINE CTR WESTERN WASHINGTON UNIV	ANACORTES	WA
641	SMITHSONIAN TROPICAL RESEARCH INSTITUTE	BALBOA	PANAMA
190	UMCES/CHESAPEAKE BIOLOGICAL LABORATORY	SOLOMONS	MD

477 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
540 DUKE UNIV MARINE LAB-MARINE MAMMALS LABS	BEAUFORT	NC
1060 MARINE BIOLOGICAL LABORATORY	WOODS HOLE	MA
960 MARINE ECOSYSTEM RES LAB,GRAD SCH OCEANOGRAPHY,URI	NARRAGANSET	RI
646 SMITHSONIAN TROPICAL RESEARCH INSTITUTE	BALBOA	PANAMA
656 SMITHSONIAN TROPICAL RESEARCH INSTITUTE	BALBOA	PANAMA
758 THE OCEANIC INSTITUTE	WAIMANALO	HI
49 UNCW CENTER FOR MARINE SCIENCE RESEARCH	WILMINGTON	NC
822 VA INST OF MARINE SCIENCE, COLLEGE OF WILLIAM&MARY	GLOUCESTER PT	VA
737 WILLIAM W. KIRBY-SMITH/DUKE UNIVERSITY MARINE LAB.	BEAUFORT	NC
551 BERMUDA BIOLOGICAL STATION FOR RESEARCH	ST GEORGES	BERMUDA
570 BERMUDA BIOLOGICAL STATION FOR RESEARCH	ST GEORGES	BERMUDA
464 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
485 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
491 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
508 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
526 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
214 CENTER FOR GREAT LAKES STUDIES	MILWAUKEE	WI
473 CNTR FOR COASTAL STUD., TEXAS A&M U-CORPUS CHRISTI	CORPUS CHRISTI	TX
622 COOPERATIVE OXFORD LABORATORY	OXFORD	MD
881 DAUPHIN ISLAND SEA LAB	DAUPHIN ISLAND	AL
904 DAUPHIN ISLAND SEA LAB	DAUPHIN ISLAND	AL
1024 FLORIDA MARINE RESEARCH INSTITUTE	ST. PETERSBURG	FL
755 INST. OF MARINE SCI.-LONG MARINE LAB.-UNIV OF CA	SAN CRUZ	CA
718 LARGE LAKES OBSERVATORY	DULUTH	MN
248 LYLE S. ST. AMANT MARINE LABORATORY	BATON ROUGE	LA
1127 NOAA, CHARLESTON LABORATORY	CHARLESTON	SC
1016 PRINCE WILLIAM SOUND SCIENCE CENTER	CORDOVA	AK
768 THE OCEANIC INSTITUTE	WAIMANALO	HI
919 UNIV OF TEXAS MARINE SCIENCE INSTITUTE	PORT ARANSAS	TX
931 UNIV OF TEXAS MARINE SCIENCE INSTITUTE	PORT ARANSAS	TX
1035 UNIV OF TX-PAN AMERICAN COASTAL STUDIES LAB	SOUTH PADRE IS.	TX
519 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
457 CNTR FOR COASTAL STUD., TEXAS A&M U-CORPUS CHRISTI	CORPUS CHRISTI	TX
982 ROMBERG-TIBURON CENTER FOR ENV. STUDIES	TIBURON	CA
787 SKIDAWAY INSTITUTE OF OCEANOGRAPHY	SAVANNAH	GA
788 SKIDAWAY INSTITUTE OF OCEANOGRAPHY	SAVANNAH	GA
544 UNIV TEXAS MARINE SCIENCE INST	PORT ARANSAS	TX
237 BLAKELY ISLAND FIELD STATION	SEATTLE	WA
536 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
667 S.C. MARINE RESOURCES DIVISION	CHARLESTON	SC
683 S.C. MARINE RESOURCES DIVISION	CHARLESTON	SC
500 CENTER FOR COASTAL STUDIES	CORPUS CHRISTI	TX
1043 MARINE BIOLOGICAL LABORATORY	WOODS HOLE	MA
4 NATIONAL MARINE FISHERIES SERVICE	PANAMA CITY	FL
1096 NOAA-BEAUFORT LABORATORY, SEFSC	BEAUFORT	NC
1112 NOAA-MISSISSIPPI LABORATORIES- SEFC	STENNIS SPACE CENTER	MS
678 S.C. MARINE RESOURCES DIVISION	CHARLESTON	SC
712 WMFS MFS - MISSISSIPPI LABORATORIES	STENNIS SPACE CENTER	MS
44 HARBOR BEACH OCEANOGRAPHIC INST.	FT. PIERCE	FL
70 MOTE MARINE LABORATORY	SARASOTA	FL
112 MOTE MARINE LABORATORY	SARASOTA	FL
124 MOTE MARINE LABORATORY	SARASOTA	FL

The data is available in a shared Internet database called Labnet (for further information, see <http://www.mbl.edu/html/NAML/brochure/LABNET.brochure.html>).

## Conclusions and Recommendations

Salinity is an important, fundamental property of seawater in the coastal zone. Salinity:

- \$ Directly affects biological and physical processes.
- \$ Serves as an inexpensive, easily measured proxy for more expensively detected pollutants (tracking sewage outfall plumes, excessive estuarine and river outflow).
- \$ Provides critical information on processes related to ecosystem function and human impacts.
- \$ Can be measured easily and economically with routine maintenance and calibration.

While it was determined that salinity should be measured at locations to provide insight into regional processes such as river plumes and coastal currents, it is necessary to consider ease of maintenance and instrument stability and survivability. Further development of *in situ* and remote measurement techniques is required to address these constraints.

Platforms of opportunity such as NOS PORTS<sup>Ô</sup> sites, NDBC C-MAN and coastal buoys, and COE remote terminal units are logical locations for salinity measurements. They are located in bays, estuaries, harbors, near coastal waters, and on the shelf. All of these are remote stations with telemetered data. States such as Texas and Washington maintain coastal and estuarine stations and thus provide platforms for salinity measurements.

Fouling is a fundamental technical challenge in making salinity measurements. Both the technical challenge of finding effective anti-fouling materials and the regulator issues related to using these materials need coordinated assistance and possible state and federal legislative assistance.

The workshop recommends the creation of a nationally recognized effort to coordinate monitoring of salinity at specific locations along the United States coastline. The coordination would provide the following:

- \$ Information on technical issues such as fouling
- \$ Comparative information on sensor systems
- \$ Coordination of calibration
- \$ Information on and location of available data
- \$ Framework and testbed for sensor development

## \$ Development of archiving scheme for data at NODC

### References

- Berger, R.C., McAdory, R.T., Martin, W.D., and Schmidt, J.H., 1995. Houston-Galveston navigation channels, Texas project. Report 3, Three-dimensional hydrodynamic model verification. U.S. Army Corps of Engineers, Waterway Experiment Station, Technical Report HL-92-7
- Bergman, T, 1784. Physical and chemical essays (translated by Edmund Cullen) Murray, London, 2 vol.
- Birch, T. (ed.), 1965. The works of Robert Boyle. Georg Olms, Hildesheim, 6 vol.
- Boyle, R. 1693. An account of the honourable Robert Boyle=s way of examining waters as to freshness and saltneßs. Phil. Trans. Roy. Soc. Lond., 17, 627-641.
- Cox, C.A.. 1963. The salinity problem. Progress in Oceanography, 1, 243-261.
- Dittmar, W. 1884. Physics and Chemistry, Rept. Scient. Res. H.M.S. *Challenger* 1873-76, 1, 251 pp.
- Emery, W.J. and R.E. Thomson. 1998. Data Analysis Methods in Physical Oceanography. Pergamon Press, New York, 634 pp.
- Gay-Lussac, J. L.. 1717. Supplement a la note sur la salute de la mer, imprimée dans le sixieme volume des Annales de Chimie et de Physique. Ann. Chim. Phys. Ser. 2.7.79-83.
- Hamon, B.V.. 1955. A temperature-salinity-depth recorder. Conseil Permanent International pour le Exploration de la Mer. Journal de Conseil, 21, 22-73.
- Hamon, B.V. and N.L. Brown. 1958. A temperature-chlorinity-depth recorder for ue at sea. J. Scientific Instru., 35, 452-458.
- Johnson, B.H., Heath, R.E., Hsieh, B.B., and Kim, K.W., and Butler, H.L., 1991. Development and verification of a three-dimensional numerical hydrodynamic, salinity, and temperature model of Chesapeake Bay. V. 1, U.S. Army Corps of Engineers, Waterway Experiment Station, Technical Report HL-91-7
- Knudsen, M. 1901. Report 2em Conf. Int. Explor. Mer, Kristiania, 1901, 38 pp.
- Knudsen, M., C. Forch and S.P.L. Sorensen. 1902. Bericht über die chemische und physikalische Untersuchung des Seewassers und die Aufstellung der neuen hydrograohischen Tabellen Wiss. Meeresunters, n.f., 6, 13-184.
- Lavoisier, A. 1772. Memoire sur l=usage de >esprit-de-vin dans l=analyse des eaux minerales, Mem. Acad. Roy. Sci.(Paris), 1772, 555-563.
- Lewis, E.L. 1980. The practical salinity scale 1978 and its antecedents. J. Oceanic Engineering, 5, 3-8.

Miller, J.L., M.A. Goodberlet, and J.B. Zaitzeff. 1998. Airborne salinity mapper makes debut in coastal zone. EOS, Trans., Amer. Geophys. Union, 79(14), 173-177.

Murray, J. 1818. An analysis of sea water; with observations on the analysis of salt brines. Trans. Roy. Soc. Edinb., 8, 205-244.

Schmalz, R.A. 1996. National Ocean Service Partnership: DGPS-supported hydro survey, water level measurement, and modeling of Galveston Bay. NOAA technical Report NOS OES 012

Schmalz, R.A., Devine, M.F., Richardson, P.H., 1994. Residual circulation and thermohaline structure. Summary report, V. 2, Long Island Sound Oceanography Project, NOAA Technical Report NOS OES 003

van Oort, R.C., J.J.C. van Spronsen and P. Vergurgh. 1998. Monitoring instruments for conductivity and temperature, Werkdocument RIJKZ-98.009, 20 pp.

Wallace, W.J. 1980. The development of marine chemistry until 1900. In Oceanography: The Past, M. Sears and D. Merriman, Eds., Springer-Verlag, New York, 337-343.

Wang, H.V., Johnson, B.H. and Cerco, C.F., 1998. The Chesapeake Bay experience. Proc. Estuarine and Coastal Modeling conference, 16-25

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